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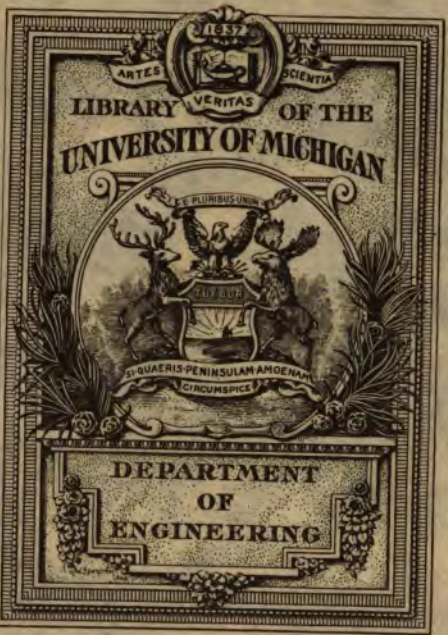
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PRACTICAL DIRECTIONS

FOR

WINDING MAGNETS

FOR DYNAMOS.

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WINDING MAGNETS

FOR DYNAMOS.

By CARL HERING.

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1892.

PREFACE.

WHILE engaged in remodelling, improving, and standardising the dynamo machines manufactured by a large firm in Germany, the writer felt the need of some reliable method for examining the machines with a view to finding their best proportions, and also of some method for calculating the windings for the field magnets, especially for shunt and compound wound machines. The methods heretofore used were either based on purely theoretical deductions, and were therefore of little practical value, or else they were inaccurate or cumbersome and unreliable.

The method described in these articles was devised to meet the requirements of engineering practice, and to obviate as much as possible the objectionable factor of empiricism. Although far from perfect, it will at least serve as a guide until some more complete method is devised and thoroughly tested by its application to practice.

The greater part of these articles was first published in the 'Electrical World,' of New York. They have, however, been revised, enlarged, and in many parts rewritten entirely.

CARL HERING.

PHILADELPHIA, U.S.A.

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PRACTICAL DIRECTIONS

FOR

WINDING MAGNETS

FOR DYNAMOS.

CHAPTER I.

Introductory.

In designing a dynamo for generating a certain definite potential and current, it is difficult, if not impossible, in most cases to calculate all its parts with any great degree of accuracy, as there are a number of proportions which depend on quantities varying very greatly in their values. Among these quantities are chiefly the magnetic qualities of the iron used, the effect of the shape of the magnetic parts, the air space in the magnetic circuit, the magnetic leakage around the outside of the magnets and of the armature, the variable resistance-equivalent of the self-induction of the armature and field magnet coils, the effect of the number of pulsations or armature coils, the Foucault currents in the armature core and in the pole-pieces, the counter magnetism of the armature, and the retardation of its magnetism, commonly called the magnetic lag. Until it is known how these affect the electromotive force and current quantitatively, it will be impossible to make any accurate calculations of the most economic size of all the different parts of a dynamo for generating a certain definite electromotive force and current. It is known, however, that under certain con-

ditions easily obtainable in practice, the effect of a number of those quantities or proportions on the electromotive force and current is so small that it may be neglected. The effect of certain others will be approximately the same in machines of different sizes but of the same general proportions.

'The quantitative relation between the ampère-turns of the field magnet coils and the useful lines of force entering the armature, for differently shaped magnets, is still a factor about which very little, if any, definite and reliable information has been published. Recent investigations* in apparently the right direction may, however, lead to the determination of certain reliable constants and relations, which will materially aid the engineer in calculating more nearly the relations between the exciting current and the field intensity, without first constructing a number of trial machines.

If the size of a field and its intensity in gausses or in number of lines of force per square inch were known, the calculation of a well-proportioned armature to be used with this field, and to give a certain definite electromotive force and current, would not be difficult, for it is known that a wire cutting lines of force at the rate of 100,000,000 per second will generate one volt. This, together with the consequent length, the allowable resistance and the necessary cooling surface, will enable one to make a tolerably accurate calculation of the number of turns, the size of the wire, and in general, all the proportions of the armature, provided it is designed so that the objectionable factors, such as the self induction, the counter magnetism, the sparking, etc., may be made small enough to be neglected, or allowed for by a small "factor of safety."

If the machine to be designed does not differ greatly in shape and general proportions from a finished machine, which may be tested and used as a model, it is not difficult to calculate approximately its proper proportions if it is

* Kapp, 'Proceedings of the Society of Telegraphic Engineers,' November 11th, 1886.

assumed that the field intensity is the same. The armature may be readily calculated, even for an electromotive force and current differing considerably from those of the model machine. The magnets may be calculated from the total amount of magnetism required, which is determined by the intensity per square inch, and the number of square inches of core and of pole-piece surface required by the new armature, remembering that every line of force requires the same cross section of iron, that is, that the cross section of the cores of the field magnets, as well as that of all the other iron parts in the circuit of the lines of force, should be increased in the same proportion as the total number of lines of force. Suppose for example that from the calculation of the armature it is found that the field, of the same intensity, should have double the area of that in the model, that is, the pole-piece surface should be twice as large, then the number of field magnets of the same size and winding would have to be doubled, that is, there would have to be two magnets to every one in the model. But it is objectionable on account of economy of wire, winding, and machine fitting, to have several small parallel magnets terminating in the same pole-piece, and, therefore, it is preferable to combine the two magnets into one. This large core must, therefore, have about twice the cross section of core in order to be equivalent magnetically to the two smaller ones.

If in testing the model machine it is found that the cores are too large or too small, or the winding too deep, or if the heating of the magnets is too great, it is best to find first, what the proper sizes should be for this model machine, and from these corrected dimensions determine those of the new machine.

Should the new magnets require wire of different size, as for instance when both are shunt machines of the same potential, or series machines with a different current, a correction should be made for the insulation. As a guide to determine this correction it may be assumed that the external cooling surface of the magnet coils should be

proportional to the watts consumed in the coils, in order that the magnets should not heat any more than those of the model machine. For the same cross section of the coil space perpendicular to the wire, and for the same external cooling surface, it is evident that it makes no difference, as far as the heating is concerned, what size of wire is used, nor what the thickness of the insulation is, as long as the watts consumed in it are the same, because the heat generated and the cooling surface then remain the same. It is often necessary to take into account also the resistance of the coils and their current, besides the watts consumed, and, therefore, the wire will generally be limited to one particular size for each machine, as will be shown in the following chapters.

For the same cores and external cooling surface, and the same ampère-turns obtained in the one case by a smaller wire of more turns, and in the other case by a larger wire of fewer turns, it may in general be assumed that that portion of the whole transverse cross section of the coil which is copper, should remain the same or approximately so. It is, therefore, necessary to increase the space allowed for the coil, when fine wire is used, by the amount occupied by the larger proportion of insulation. This correction factor may be readily determined by winding a small spool with the coarse wire, and a similar one with the fine wire to the same depth. From the number of turns on these spools and the size of the wire, calculate the cross section of copper in each one. The cross section of the coil spaces being the same, it may then be readily determined by a simple proportion what the space should be for a fine wire coil having the same cross section of copper as the coarse one. For example, suppose the cross sections of copper in two spools of the same volume, to be 10 and 5 respectively, then it is evident that the space or volume of the finer coil should be twice that of the other in order to have the same cross section of copper in it. In general the cross section of two coil spaces should be inversely as the cross section of copper of two equal volume coils.

The increased space for a fine wire coil should preferably be allowed for in the length of the core and not in the depth of the winding or thickness of the coil, unless the correction is small, as the depth should be a constant proportion of the mean diameter of the core, and it is assumed in the above-mentioned rule that the mean length of one winding remains the same.

These calculations will enable one to determine approximately the size of the magnet cores and coil spaces, and the winding required for a new machine to generate a certain definite electromotive force and current with a predetermined armature. But as quite a number of factors were neglected, the finished machine may give a potential or current differing materially from what was desired. It is necessary therefore to allow what might be called a factor of safety, that is, to make the magnets slightly larger than the calculation requires, in order to be sure of obtaining at least the desired result. The final adjustment of the finished machine may then be made by increasing or diminishing the speed by the amount required.

It will frequently be found, however, that as regards the winding of the coils, this method will give unsatisfactory results, and that the probabilities are that the necessary speed obtained from the final experiment will either be too high to make the machine safe and durable, or that it will be too low to give the required efficiency for the size and cost of the machine. Such a method will be especially unsatisfactory if it is desired to construct the machine of the best possible proportions, while for compound machines it will be almost impossible to obtain any reliable results. In such cases the methods described in the following chapters will be found to be very little more trouble, and will in all cases enable the winding of the predetermined cores to be calculated with all due precision, and at the same time will afford an easy means of ascertaining the best or the cheapest proportions.

CHAPTER II.

Preliminary Tests.

In determining the proper winding of machine magnets it is necessary to comply with the following conditions:—That in the finished machine the necessary speed is not too high to be safe and practicable, or too low to obtain the best efficiency in the machine; that the brushes may be placed in the position of least sparking; that the magnet coils have the proper resistance, in order that they absorb the proper percentage of energy allotted to them, and that the cost of the wire on the magnets is not too great; that for shunt machines, the resistance is not too great to enable the proper exciting current to flow through the coils; that the number of watts generated is not too small in proportion to the size and cost of the machine; in general, that the proportions are the most economic and most efficient under the circumstances.

The following method affords a sure and tolerably exact means for determining the proper winding in compliance with these conditions, thus eliminating entirely the factors of uncertainty, or of good or bad guessing.

The greatest current which a machine will be able to maintain continually depends on the size of wire of the armature, on the amount of its heat radiating surface, and on the number of watts consumed in the armature itself. In general, therefore, the current is limited by the armature; this having been constructed, the maximum current is fixed and determined by it. There remains then to construct a field, in which this armature will, at the proper speed, develop the desired electromotive force while the previously determined current is flowing through it.

The speed of the armature depends only on its mechanical construction, and is therefore limited by it. As an increased

speed signifies a direct gain in some other proportions, it is evident that it should be made as high as it is practically safe and advisable to run the armature continually with a full load on the machine. It is also assumed here that the field magnet frame has been designed and constructed so as to meet, as well as it is possible to predetermine it, the requirements of the field.

As the electromotive force depends upon the speed, the number of windings on the armature, the size of the armature, and the magnetism of the field magnets, it is evident that if the armature and frame are constructed and the speed determined upon, the only thing left to vary, in order to make the armature give the required electromotive force, is the magnetism of the field magnets.

In order to determine this, erect the machine with its proper armature, run it at its proper speed with some temporary coils on the magnets, being careful to note the exact number of turns of wire on these coils. While running the machine at its proper speed, discharging the current from the armature directly into a large rheostat, a battery of lamps, a tub of acidulated water, or secondary batteries, excite the field magnets with the current from another machine or secondary battery. Increase or diminish this exciting current, and regulate the rheostat in which the current is absorbed until the current delivered by the armature is the proper strength and has the required potential, when the brushes are set to the least-sparking position. It is evident that this will enable one to properly adjust all the parts and conditions, and will allow of any slight changes of speed, or other changes, which the running of the machine may show to be necessary. When it is running properly and has been "warmed" sufficiently, measure the exciting current.

The intensity of a field is proportional to the ampère-windings or ampère-turns on the several magnets, that is, to the number of ampères flowing through the wire multiplied by the sum of the number of turns on all the magnets. It is immaterial whether the current be large and the number of

turns small, as in a series machine, or *vice versâ*, as in the shunt machine, or whether it be a combination of both, as in a compound machine, if only the product of the current into the number of turns be the same.

The measurement made as above described will, therefore, if the ampères of current be multiplied by the number of windings in the coils, give the proper ampère-windings required to make the machine generate the desired electromotive force when delivering the proper current at the proper speed. It remains only to calculate the correct size of the wire and the number of its turns, from this given quantity of ampère-windings, in order that the finished machine may have the required intensity of magnetic field, that is, the same ampère-windings. This size of wire will, of course, depend on whether it is a shunt, series, or compound machine, also on the allowable current or fall of potential in the magnet coils, on the cost of the wire, etc. The formula for determining the size of the wire for these three special cases, will be given in the subsequent chapters; there will be discussed here, only such other points as apply to all machines, independently of the nature of their winding.

The temporary coils may be wound on a shell of common tinned iron or of brass, and made to fit the magnet cores. They must all have the same number of windings, and had better be connected in series, for if they are in parallel arc one is never sure, unless the resistances are exactly equal, that they have the same current, and it is difficult to get both the resistance and number of turns exactly the same in all. They should be wound to about the same depth as the finished magnets will probably be, in order to eliminate any difference in the mean distance from the wire to the iron. The size of the wire of these temporary coils depends upon the machine or battery which is at the disposal of the constructor to be used for the exciting current. If this exciting-machine gives a small current of high potential, use tolerably fine wire; if it gives a low potential and a strong current, use thick wire. In all cases, it is best to make

a rough preliminary calculation for the size of this wire, so as not to be baffled by the incapacity of the exciting machine.

In the absence of an exciting machine or battery, the temporary coils may be supplied from the machine which is being tested, either by a shunt current from it into the coils, or by connecting them as series coils in the main circuit. In the former, a preliminary calculation should be made for the size of the wire, in order that the temporary coils do not have too great a resistance to take the proper exciting current. An adjustable rheostat should be placed in series with these coils, to regulate the shunted current. In the second case, in which they are connected as series coils, the number of turns should be made sufficiently great to ensure the obtaining of the required magnetism. An adjustable rheostat should, in this case, be placed as a shunt to the magnet coils in order to vary and adjust the exciting current. In the first case, the armature must be credited with the current shunted off into the temporary coils, and in the second case the electromotive force of the machine must be measured at the poles of the armature and not at the poles of the machine, as there is a loss of potential in the magnets.

There is, naturally, a practical limit to the magnetism which can be generated in the given cores and pole-pieces, owing to the fact that the iron becomes saturated. This limit ought, in practice, not to be exceeded, for if it is, the magnetism becomes expensive as regards the energy consumed. Some practical values are given by different authorities regarding this limit, but they should be used only as a guide. One of these is, to proportion the core of each magnet so that for every square centimetre of core there are about 110 ampère-windings in its coil, which is equivalent to 710 ampère-windings per square inch of core. This is, probably, for round wrought-iron cores. The writer found in certain machines with cast-iron oval magnets, 37 ampère-windings per square centimetre, or 240 per square

inch, to be about the safe and economical maximum. Of course, more than this could be taken, but it is not to be advised, for the magnetism then no longer increases in proportion to the ampère-windings. On the other hand, to assume much less than this, makes the machine uselessly heavy and large.

This constant applies only to the more common forms of field magnet frames, such as the Weston or Edison, consisting of simple or compounded U shaped magnets with coils on each of the two arms. For some of the less frequently used forms of frames it will be approximately some multiple of this, as will be seen from the following principles. Every part of a wire conveying a current in the coil of a magnet is encircled by lines of magnetic force, of which those that pass through the armature are rendered useful. In following the course of these lines—whose circuits are always closed, that is, they have no ends—it will be noticed that most of those generated by one of the two magnets of, for instance, an Edison machine, must return through the core of the other magnet, or in other words, each coil tends to saturate both of the cores of the magnets. This may be more readily explained by the fact that the two magnets of an Edison machine are really the two parts of one and the same U magnet, or they may be considered as one bar magnet bent at its middle to bring the two poles nearer together. In the same way a Weston machine may be said to consist of two such U magnets with their two north poles terminating in one piece and the two south poles in the other. This is also the case with the Brush, Jenney, Crompton, Siemens, Schuckert and many other machines with four magnet coils. The Thomson-Houston, Van Depoele, Hochhausen, and like types, may also be considered as magnetically equivalent to a pair of U magnets with the coils wound around the two pole-pieces which the magnets have in common. The Mather type is quite different from these in this respect, as the entire U magnet is wound with but one coil. Another distinct type is

found in the McTighe machine, in which the two U magnets contain each only one coil at what is frequently called the neutral part of the magnet. It might be compared to a Weston machine, in which the two coils of each of the U magnets are placed together as one, on the end pieces or supports, or so-called neutral parts of the two magnets.

The constant above referred to would, therefore, be quite different for some of the less frequently used types of magnets, unless it is taken as expressing the number of ampère-windings on one whole U magnet (from pole to pole) divided by the cross section of the core of that magnet, or, in other words, if it expresses the allowable number of ampère-windings per square inch of core on one complete U magnet. If used in this sense it ought to be about the same for all types of magnets, and would evidently be twice as great as at first given, or about 500 for a Weston type of machine. If the constant, taken in the sense as first described, were 250 for the Weston type, it would, if other conditions were eliminated, be 250 in the Thomson-Houston type and 500 in the Mather and McTighe types of magnet frames.

As iron becomes saturated when a certain amount of magnetism passes through every square inch cross section, a better constant than the one just given, would be the number of lines of force which may be passed through every square inch cross section of core at saturation. This would overcome the objection to using the number of ampère-windings per square inch, as this is not the same for all sizes of coils, which is due to the fact that, when the cross section increases, the intensity of magnetisation diminishes for the same current. The constant may, however, be safely used, if, as will be described, it is determined for each case. It will be found preferable to the other one just suggested, as it simplifies calculations.

The following figures may serve as a guide in determining the sizes of the pole-pieces and the cores. Fleming*

* 'Short Lectures to Electrical Artisans,' p. 18.

states that the greatest number of lines of force which a long bar of soft annealed iron can have is about 18,000 lines of force per square centimetre cross section: this is equivalent to about 116,000 per square inch. This agrees quite well with a figure given by Kapp,* for the maximum number of lines of force which can, with an unlimited magnetising power, be forced through a magnet core; for field magnets of hammered scrap he states that this is 18 units of 6000 lines each, per square inch, which is equal to 108,000 lines of force. Fleming states that in the best dynamos there are 6000 to 10,000 lines of force per square centimetre (equal to 38,500 and 64,500 per square inch), which we presume applies to the core and not to the field. In a number of the best Edison and Weston incandescent light machines, the writer found that the intensity of the field was from about 18,000 to 26,000 useful lines of force per square inch.†

As the magnetisation varies less with a varying magnetising current, after the point of saturation is reached, some makers prefer to run their machines over-saturated, because then the current delivered by them is steadier for slight variations in the magnetising current; in other words, the machine is less apt to change its electromotive force for slight changes in the external resistance. When they are over-saturated it is at the expense of the energy consumed by the magnets, and the point of saturation should therefore not be exceeded any more than is necessary to obtain this steadiness.

The size of the core being given, the limit of the ampère-windings can easily be determined from the above-mentioned constant, and it should not be exceeded, at least not much, unless the iron is particularly good. As the economic density of the magnetism, or the saturation limit, depends to such a great degree on the iron used, it is better, in all cases where the constructor has the opportunity, to find the proper

* 'Proceedings of the Society of Telegraphic Engineers,' November 11th, 1886.

† 'Electrician and Electrical Engineer,' New York, November, 1886.

limit himself by the following method:—With the machine just as it is in the foregoing test, with temporary magnet coils, run it at a very low speed, for instance, belting from the shaft directly; run it on open circuit with a fixed position of the brushes at about the theoretical neutral line. Connect the brushes with a volt-meter, and excite the magnets as before with the current from another machine, beginning with a small current and increasing it as high as the wire will stand, measuring in each case the exciting current and the electromotive force at the poles.

The electromotive force on open circuit is a direct representative of the magnetisation of the field, that is, the useful magnetism. The ampère-windings, that is, the exciting current multiplied by the number of windings in the coils, represent the cost of the energy to produce this magnetism. By plotting these values, a curve is obtained which represents the relation between them, and which will show up to what degree the one rises proportionally to the other. In the accompanying diagram (Fig. 1) such a curve has been plotted, the values being taken from an actual case.

The ordinates represent the ampère-windings, and the abscissas the potential. From the curve *a b* it is seen that the useful magnetism, or its representative, the potential, rises nearly proportionally with the ampère-windings up to about 27,000 ampère-windings, at the point *c*, where it takes a decidedly different direction. This point is the limit at which the useful magnetism is economically obtained, and is, therefore, the limit to which the machine should be magnetised. This is the point at which the magnets are saturated. Dividing this quantity of magnetism, or this number of ampère-turns, by the sum of the areas of cross section of all the magnet cores, gives the constant above referred to, that is, the maximum allowable density of the magnetism just before saturation. In this special case there were four magnets, each with a cross section of 181 square centimetres, giving, therefore, thirty-seven ampère-windings per square centimetre, or 240 per square inch.

The distance *o a* shows the remnant magnetism, while the part of the curve *c b* shows the increase of magnetism due to the coil itself, after the iron is saturated.

FIG. 1.

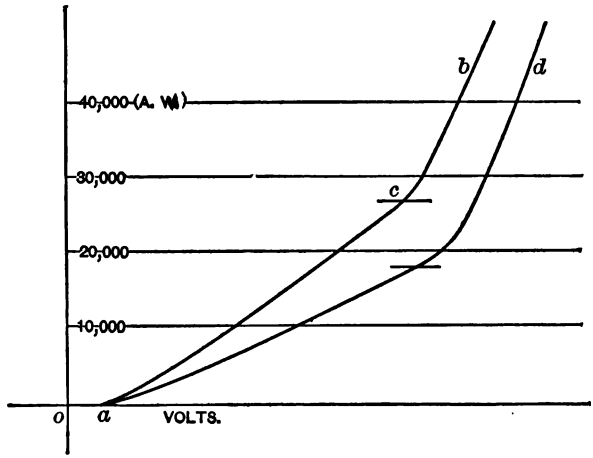


Diagram of Magnetic Saturation.

This diagram also shows a very important point to be noticed in building compound machines, to be referred to later.

The speed at which the machine must be run for this test depends, of course, on the range of the volt-meter at one's disposal. It should be so chosen, that the values for the potential are inside of the range of the instrument, which can be determined by trial. A high resistance in series may be used to reduce the values to the range of the instrument, provided no appreciable current is allowed to flow, as that would, by shifting the diameter of commutation, change the results.

Although it may hardly seem credible, yet the case has actually occurred in quite a large factory, that magnets were re-wound because the "direction" of the winding of

the coils was not the right one. It may, therefore, not be out of place here to remark that it is evidently quite immaterial in which direction the magnet coils are wound, as they can in all cases be connected correctly with each other and with the poles of the machine. It is evident that there is one right way and one wrong way, and if a certain connection is wrong it is evidently only necessary to reverse the connections of the two ends of that wire to make it right. The only advantage in winding in a certain definite direction is that the connections may then be as short as possible and have a better appearance.

It is always advisable in making the test for determining the proper ampère-windings, to examine the pole-pieces as regards their polarity, with a compass needle (being careful not to reverse the polarity of the needle in doing so), and to note it, in order that the coils of the finished machine may be connected so as to have that same polarity. Also find which is the positive and which the negative brush in the test, so that the compound connections may be made correctly before the machine runs, as much time can thereby be saved. It is evident that with certain connections of the magnets with the brushes, the machine will give absolutely no current.

CHAPTER III.

Shunt Machines.

In a shunt-wound machine the armature must supply the sum of the currents in the external circuit and in the shunt magnets. It is therefore necessary, before testing for the ampère-windings, to determine approximately what this shunt circuit current should be. In large machines it may be taken about 1·5 to 2·5 per cent. of the current in the external circuit, and in small machines for from 10 to 20 incandescent lamps, or their equivalent, it will have to be

taken as high as 10 per cent., and even higher, in order not to make the cost of the wire too great. Having determined this, approximately only, the ampère-windings of the machine are determined as above described, while the armature gives the current required for the lamps in addition to that which will be required by the shunt magnets. Let (a W) represent the magnetism in ampère-windings obtained in the test under these conditions.

It is evident that the size of the wire to be used for the magnets depends upon various quantities and conditions. For instance, it must not be too small, or the current will heat it too much. It must be large enough, in order that the total resistance of the coils be not too great to take its proper current as shunt to the machine. It must not be so large that it takes up more space than is allowed for the coils. It must not be so small that after heating, its resistance becomes too high to take its proper current. It must be so large that its resistance is such as to enable an adjustable rheostat to be placed in series with it, to regulate the machine for varying service.

From this it will be seen that it might require a very lengthy and tedious calculation to endeavour to determine the proper diameter directly from the ampère-windings, by trying different values for the current and corresponding number of ampère-windings, and calculating the resistance and size of the coils for each case, to see which wire is correct.

In order to take into consideration all these factors, and at the same time to simplify the calculations, the writer has deduced the following formulæ, which may be used to determine, by a single calculation and with certainty, what diameter will meet these conditions, thereby facilitating calculations very much, as it eliminates the element of guessing.

Let (a W) represent the ampère-windings obtained in the test,

a = current in the shunt magnets of the finished machine,

W = total number of windings or turns on all the magnets of the finished machine,

R = total resistance of the magnet coils of the finished machine, in legal ohms,

V = potential at the poles of the finished machine in volts,

d = diameter of the bare wire in mils (thousandths of an inch),

l_m = mean length of one winding in inches,

l = length, in inches, of one winding of the lowest layer, which is about the same as the periphery of the core.

It is evident that the resistance is proportional to the total length, $W l_m$, and inversely as the square of the diameter, and is equal to

$$R = 50{\cdot}13 \frac{W l_m}{d^2} \theta,$$

in which θ is the specific resistance, that is, the resistance in legal ohms of one metre of copper wire of 1 square millimetre cross section, at 0° C.; the constant 50·13 contains the reduction factors.

By Ohm's law

$$R = \frac{V}{a};$$

therefore

$$\frac{V}{a} = 50{\cdot}13 \frac{W l_m \theta}{d^2};$$

from which

$$d = \sqrt{50{\cdot}13 \frac{(a W) l_m \theta}{V}};$$

from which the diameter can be calculated directly from the ampère-windings (a W) and the potential, if the mean length of one winding is known.

The value of this mean length can be determined from the inside length l, if the thickness of the coil is known. But this thickness again depends on the number of ampère-windings, the resistance of the wire, and the thickness of

the insulation. It is possible to determine relations between all these and introduce them into this formula, thereby eliminating the unknown factor l_m, but this will be found to make the formula so complicated that it becomes practically too troublesome to use.

In actual practice so many factors enter, which are either inexact or limited to certain values, that an exact calculation has little value. For instance, the copper may have, and probably has, a different specific resistance than any figure which one might assume. An almost inappreciably larger or smaller diameter changes the resistance materially; so also the temperature to which it is raised; the sizes of wire are limited to certain fixed numbers, and the insulation has not always the assumed thickness. For these reasons, the following approximate method of using this formula will be found to be practically safe and correct, while it is at the same time much simpler.

The thickness or depth of the coil is practically limited; if it is too thin, there is more iron in the core than is necessary, or the magnets are too long, or both; if too thick, the magnets are probably over-saturated or too short, or both. Some of the older authorities say that the thickness of the coil and core can be made equal. In actual experience, however, it is found that this is far too thick for machine magnet coils, as it makes the cost of both wire and energy consumed in the magnets much greater than it ought to be. A better figure, obtained by the writer from actual practice, is, for a flat oval magnet, a maximum limit of about one-third the thickness of the core for cast-iron, or about one-half the diameter of the core if it is circular. This will be found to be more reliable in actual practice for machine magnets being based on real results, as distinguished from theoretical deductions.

The thickness being therefore limited to a comparatively small range, it is quite safe to calculate the mean length of a winding from this assumed thickness of coil, for it will be found that this mean length will vary very little for any

possible variation in the thickness. For instance, in an actual case of an oval magnet, diminishing the thickness of the coil as much as 50 per cent. decreased the mean length of one winding only 7 per cent.

Assuming, therefore, a certain approximate thickness of coil, and having given the periphery of the core, the mean length may readily be calculated as follows:—For an oval magnet, not too flat, the lengths of the inside and outside layers are in the proportion:

$$\frac{a+b}{a+b+4c};$$

in which a and b are the length and breadth of the oval cross section of the core, and c the assumed thickness or depth of the coil.

This gives for the mean length of a winding

$$l_m = l + \frac{2cl}{a+b},$$

l being the periphery of the core in inches. For a circular magnet in which the core has a diameter D, the mean length is evidently

$$l_m = \pi(D + c).$$

If it is found after completing the experiments and calculations, that the assumed thickness of coil is much too small, then it is preferable to lengthen the magnet cores so as to reduce this thickness of coil, provided the magnet cores are not over-saturated, that is, that the cross section of the core is not too small.

On the other hand, if it is found that the necessary thickness of coil is much smaller than the assumed, it shows that the magnets are probably too long.

Having now determined this mean length for an assumed thickness of coil, the diameter of the wire can be calculated directly from the formula

$$d = \sqrt{50{\cdot}13\frac{(a\ W)\ l_m\ \theta}{V}}$$

without having first to determine what current and what number of windings to take, as the known quantity (a W) enters directly into the formula.

From what has been said above, some allowance, or factor of safety, must be taken for the resistance, in order that when the coil is wound, it is not found that the resistance is a little too high to take its proper current. An allowance should also be made for introducing an adjustable resistance by which the machine may be regulated. The factor of self-induction may also enter, and will have the effect of apparently increasing the resistance, depending upon the degree of pulsation of the current, or, what is the same thing, on the number of commutator strips. In order to make allowances for all these factors, and to introduce them into the formula, it is necessary merely to diminish the value of the potential V in the formula accordingly. For ordinary cases, 10 to 15 per cent. may be allowed, but it is safer to take 20 per cent., and even 25 per cent., if considerable variation in the adjustable resistance is to be allowed for. Assuming 20 per cent., it is necessary merely to multiply the potential V by ·80, and introduce this directly into the formula in place of V.

Assuming for ordinary good copper wire a specific resistance θ equal to 0·0162 at 0° C., the formula becomes, assuming a temperature of about 70° Fahr.,

$$d = \sqrt{\cdot 875 \frac{(a\ \mathrm{W})\, l_m}{\mathrm{V}}},$$

in which d is in mils (thousandths of an inch) and l_m in inches.

If this should give a value which is too small, so as to be impractical, it shows that either the length l_m is too short, that is, the cross section of the magnet too small, or that the number of ampère-windings is very small, or that the potential is high for the required ampère-windings. In the last two cases it is necessary merely to take a larger diameter

of wire and to add external resistance in the magnet circuit.

If the formula should give a very large diameter, it shows that either the magnet cores or the ampère-windings are too large, or that the potential is very small for the required ampère-windings. If the magnets are already saturated, and therefore cannot be made smaller, then it shows that the machine is overworked, unless it happens to be a machine of low potential and great current, such as a plating machine, in which case a large value for d is quite correct.

Having determined d, it is evident that any current a could now be assumed, and the corresponding number of ampère-windings made equal to $\frac{(a\ \mathrm{W})}{a}$, which would, in all cases, give the proper ampère-windings and the proper resistance. But there are practical limits, which are quite narrow in most cases, on account of the assumed mean length l_m or the thickness c of the coil. It is necessary to be limited to this value of l_m, to a certain extent at least, in order that the resistance may not differ too much from what it should be.

The method to pursue, therefore, is as follows:—Assume a certain current a, for a large machine about 1·5 to 2·5 per cent. of the total current, and for a small machine as high as 10 per cent., and by dividing it into the ampère-windings, to obtain the number of turns, calculate the space occupied by the coil (remembering to use the outside diameter of the insulated wire), and see how near the thickness corresponds to the assumed value c. If this thickness is found to be much greater, it shows that either the machine is overworked and that the magnet current will therefore have to be taken greater to diminish the number of windings, or else it shows that the magnet cores are too short, and should be lengthened, provided they are not over-saturated. If, on the other hand, this calculated thickness c is found to be much smaller, it shows that either the machine could be run more economically, if necessary, if a smaller current be used

at the expense of an increased cost of the wire, or that the magnets may advantageously be shortened, provided they are not over-saturated.

To determine directly what the current and what the number of windings must be for the assumed thickness c of a coil, calculate the diameter of the bare wire from the formula, take the nearest gauge-number wire, and measure its diameter with the insulation, which is best done by winding, closely, ten turns around a pencil or bolt, and measuring the length of this little coil in inches; this multiplied by 100 gives the diameter of the covered wire in mils. Call this d_1. If the length of the core or of the space allowed for one magnet coil be represented by e in inches, and the number of magnet coils on the machine by n, then it is evident that the number of turns per layer for one magnet will be

$$\frac{1000\ e}{d_1}$$

while the number of layers will be

$$\frac{1000\ c}{d_1}$$

and the number of turns per magnet $\frac{W}{n}$ will be their product, that is,

$$\frac{W}{n} = 1{,}000{,}000\ \frac{e\ c}{{d_1}^2},$$

thus enabling one to calculate W directly, and consequently to determine a from $(a\ W)$, as it is evident that

$$a = \frac{(a\ W)}{W}.$$

If this current a is found to be very small, it might be more advantageous to use a stronger current with less turns of wire, and therefore less thickness of coil, in that way decreasing the cost of the magnet wire, it being no small portion of the cost of the material for the machine.

If for a large machine the field current is found to be smaller than 1·5 to 2·5 per cent. of the whole armature current, it shows that the machine has not the most economical proportions, and that, if an incandescent light machine, the same frame may be used, with an armature having thicker wire and less turns, and therefore capable of supplying more lamps; or if an arc light machine, the same frame and armature may be used to give a higher potential at the same speed, thus supplying more lamps. In general, it shows that the frame is larger than is necessary.

After finding what the current a is, it is advisable to calculate what current per square mil this will give with the ascertained diameter d, in order to guard against heating. In large magnets it should not be more than ·0013 to ·0015 ampères per square mil, which is equal to about 750 to 650 square mils per ampère. If it is found to give a greater density of current than this, it is safest either to take a smaller current and more turns, or to increase the diameter slightly. In many cases it will be found that the diameter obtained from the formula (in which it depends on the allowable resistance) will be larger than that which would be obtained if it were calculated not to heat too much; but it is always safest to calculate both and take the largest.

If the current a is found to be a large proportion of the total current, or if for the calculated diameter it is found that it will heat too much, then the machine is overworked and ought to be used for doing less work, either by using the same armature and making the machine generate less electromotive force, or by taking a different armature with more turns of smaller wire in it, thus giving the same electromotive force but less current.

Owing to the fact that in most cases some insulating material, such as card-board or thick paper, is placed between some of the layers to insure an evenness in the winding, the real thickness of the coil will be greater than that assumed in the calculation, and, therefore, the mean length and resistance will be slightly different, but this

error will in most cases be covered by the factor of safety of 20 per cent. in the allowable resistance.

For the sake of appearances the last or outside layer is always wound full, thus limiting the number of windings to certain successive numbers which are multiples of the windings in one layer. In general, however, if the number of turns be increased slightly, the resistance will thereby increase, and, therefore, the current decreased, but the product of the current into the number of turns will remain approximately the same.

If after the magnets are fully wound and the finished machine tested, it is found that owing to some small error it gives a slightly lower or higher potential, the speed may be varied to compensate for this.

Having made all the calculations for the magnets of the finished machine, it is best to check them finally by calculating the resistance from the following formula:

$$R = 50{\cdot}13 \frac{W\, l_m\, \theta}{d^2};$$

or if as before θ is taken 0·0162, and the temperature is assumed to be 70° F.,

$$R = {\cdot}875 \frac{W l_m}{d^2} = \frac{3{\cdot}5\, W\, l_m}{4d^2},$$

in which d is in mils, and l_m is the corrected mean length of a winding in inches.

From Ohm's law

$$R_1 = \frac{V}{a},$$

in which R_1 is the total resistance of the shunt circuit, including the adjustment resistance. The value which this adjustable resistance may have, is evidently

$$R_1 - R.$$

If this is found to be a negative quantity, that is, if R is greater than R_1, there has evidently been a mistake made in some of the previous calculations.

If the calculated value of R is found to be too great, owing to the fact that the gauge-number of wire taken was a little smaller than the value given by the formula, then it is quite safe to take the next size larger and keep about the same number of windings, or else to modify the number of windings accordingly, and then calculate R again as a check. It is quite safe to take a slightly larger diameter of wire and the same number of windings without any fear of increasing the resistance, for, from the formula for R, it will be seen that it increases only slightly with an increased value for l_m, but decreases much more rapidly for a larger value of d.

If it is desired to regulate the machine for supplying the same potential to less lamps, by adjusting the resistance included in the magnet circuit, it is evident that it is only necessary to increase this resistance the proper amount, which can be done after the machine is finished, as it will change nothing in the preceding calculations.

If the machine is for arc lights in series, and it is desired to be able to regulate it to supply less lamps, it will be necessary to make the test for the maximum, minimum, and mean number of lamps, and then to make the resistance of the wire so low that in either case it is not too high to take its proper current, as required by its ampère-windings for that particular potential.

Finally the total length of the wire, in feet, for all the magnets may be calculated from the formulæ

$$L = \frac{W\, l_m}{12} = \cdot 0833\ W\, l_m.$$

To illustrate the calculation of shunt magnet coils by the above described method, let us assume that a certain machine with a given cylindrical armature and a frame with four cast-iron oval magnets, is required to supply 100 lamps of ·7 ampères each, that is, 70 ampères, and 100 volts. The speed is to be 1200 revolutions.

Upon running the machine with four temporary magnet

coils of 250 turns each, it was found to require an exciting current of 40 ampères to induce in the armature 100 volts, and a current of 70 + 2·5 per cent. of 70, which is equal to about 72 ampère. This gives $250 \times 4 \times 40 = 40{,}000 = (a\ \mathrm{W})$, a measure of the magnetism.

The dimensions of the oval cross section of the magnet cores were 9 inches by 3 inches. In order to determine the mean length of a winding, assume temporarily a maximum thickness of coil, one-third of 3, or 1 inch. The periphery of the core was measured and found to be 20 inches. This gives a mean length of one winding.

$$l_m = l + \frac{2\,c\,l}{a+b} = 23{\cdot}3 \text{ inches};$$

therefore from the formula

$$d = \sqrt{\cdot 875\,\frac{(a\ \mathrm{W})\,l_m}{\mathrm{V}}}$$

assuming a factor of safety of 20 per cent., that is, taking V equal to 80 volts instead of 100, the value of d is

$$d = 102 \text{ mils},$$

which is approximately equal to a No. 10 wire B. & S. (or about a No. 12½ B.W.G.)

Suppose this has an outside diameter of 125 mils. From the formula given above, the length of the core being 10 inches, there will be 80 windings per layer on each magnet, and 8 layers and, therefore, $640 \times 4 = 2560$ windings in all. This gives $\frac{40{,}000}{2560} = 15{\cdot}6$ ampères in the coils. This very large current, which is 22 per cent. of the current in the external circuit, shows that the machine is very much overrated, and that it would not be economical and even hardly possible, to finish the machine for 70 ampères and 100 volts. The heating would also be too great, as 15·6 ampères in a No. 10 B. & S. wire is ·0019 ampères per square mil, which is too great. Furthermore the core is

more than saturated, for its area of cross section is about 21 square inches, which gives for 10,000 ampère-windings per magnet, 475 per square inch, which, as compared with the constant 240, is far too great. Suppose the curve of magnetisation was found by the test to be *a d* Fig. 1, it will be seen that at 40,000 *a* W the magnets are very much over-saturated. This curve would have been sufficient, in practice, without the above calculation, to show that the machine was overrated, but for the sake of illustration, the calculations were also made.

From these figures, and from what was said above, it will be seen that the cores would have to be altered in order to use these magnets with this armature. As they are over-saturated, they will have to be increased in cross section. For a proper percentage of current in the magnets, the large number of windings necessary would make the thickness *c* of the coil much larger than it ought to be, from which it follows that the new magnets must also be made longer. In other words, these magnets have shown themselves to be much too small for that armature, or else the armature has too few windings on it for these magnets.

The same machine was then run with another armature, which has more turns of thinner wire, the size of the wire being such as to stand a current for 70 lamps. Another armature might have been made with the same size of wire, but with more layers, thus supplying about the same number of lamps; but this increases the percentage of loss of energy in the armature; it also increases the lead of the brushes, the self-induction, and sparking.

Suppose the test with the new armature gave 18,000 ampère-windings; then the following values would be obtained directly from the formulæ:

d = 67·8 mils = about No. 14 B. & S.
(or about No. 16 B.W.G.)
(d_1 = about 88 mils.)
W = 110 × 11 × 4 = 4840.
a = 3·7 ampères.

The density of current in the wire would be ·00115 ampères per square mil, and therefore, as compared with the constant given above, it is safe against heating too much. The density of magnetism in the cores would be 214 ampère-windings per square inch, which is inside of the limit. The curve of magnetism, which will naturally be the same as before (except that it has a different scale for the abscissas or volts, which does not affect the saturation), shows that for 18,000 ampère-windings the magnets are not quite saturated.

The resistance will be

$$R = \cdot 875 \frac{W\, l_m}{d^2} = 24 \text{ ohms},$$

leaving for an adjustable resistance,

$$\frac{V}{a} - R = 27 - 24 = 3 \text{ ohms}.$$

The reason why this is so small is, because the resistance of the coils is slightly greater than required by the formula, it being 24 ohms, which is due to the fact that the smaller size wire, No. 14, was selected, which is 64·08 mils diameter, that being the nearest to the calculated value of d, namely 67·8. If the next size larger than 67·8 mils is taken, that is, No. 13, the resistance would be much less, but at the same time the current a would be greater, as there would then be less turns for the same allowable thickness of coil.

If this adjustable resistance of 3 ohms is thought to be too small to admit of the proper regulation or adjustment, the speed may be increased a little, or the next size larger wire, No. 13, might be taken.

As the density of magnetism in the core is shown to be 214 ampère-windings per square inch, it will be seen that in a second machine of the same type, the cross-section of the magnet cores may be decreased slightly, thereby diminishing l_m, which decreases d; this in turn increases R and

decreases a, thus diminishing the cost of the wire and the cost of the energy to supply the magnets. The cross section of the magnets may be decreased to such an extent as to bring the density of magnetism up to the saturation point, as given by the curve.

The constant 214 also shows that the same machine may be run at a less speed, or it may be used to give a higher potential, or that the same frame may be used with an armature having a few turns less and slightly thicker wire, thus supplying more lamps.

As the density of the current in the wire is below ·0013, the first cost of the machine may be diminished at the expense of the efficiency, by taking more current in the magnets, and less windings, and therefore less wire.

By a similar course it will often be found, from the results of such a test and the deductions made from it, that certain improvements can be advantageously made in the machine.

CHAPTER IV.

Series Machines.

The calculations of the windings for series machine magnets will be much simpler than those for shunt machines, for having given the number of ampère-windings and the ampères, there is no alternative but to make the number of windings $\frac{(a\ W)}{a}$. A few hints, however, in regard to the details may lead to a better proportioning of the parts, and to results which, under the conditions, are the best possible.

It is evident that in series machines there is a loss of potential as the current passes through the magnet coils. The current being the same in the whole circuit, the loss of

potential will represent the proportion of power lost in the magnets. This, as with the current in the shunt machine, may be taken at 1·5 to 2·5 per cent. of the total, for large machines, and 10 per cent., or even more, for small or cheap machines.

Proceed with the test for determining the ampère-windings in the same manner as described for shunt-machines, except that in this test the field magnets should be excited until the desired current delivered by the machine has the required potential in addition to that which will ultimately be used up in the magnets, that is, the required potential for the lamps and leads, *plus* 1·5 to 2·5 per cent. of this potential, the current strength remaining the same. Call the number of ampère-winding thus determined (a W).

Continue the test to determine the curve of magnetism in the same way as before, in order to see whether the machine is properly proportioned, and if not, how to find its proper proportions; also to see whether the machine can be used for supplying more lamps or whether it is overworked.

Having given (a W), and as the whole current passes around the magnets, the number of windings will be

$$W = \frac{(a\ W)}{a}.$$

It remains now to find what the diameter of the wire must be in order that the loss of potential in the coils shall not exceed the allowable amount and that the coils may be wound full, for the sake of appearance. It should also be sufficiently large that it will not heat too much.

The resistance of the coils will be, as stated in considering shunt machines,

$$R = 50{\cdot}13\ \frac{W\ l_m\ \theta}{d^2}$$

in which,

R is the sum of the resistances of all the magnets, in legal ohms;

W, the total number of windings on all the magnets, when finished;

l_m, the average length of one winding, in inches;

d, the diameter of bare wire in mils;

θ, the specific resistance (metric) at the allowable temperature of the magnet coils.

The current being a, and letting the allowable fall of potential in volts be represented by v, the resistance will also be, from Ohm's law,

$$R = \frac{v}{a}.$$

Combining those two and finding the value of the diameter, gives as before

$$d = \sqrt{\frac{50 \cdot 13 \, (a \, W) \, l_m \, \theta}{v}}$$

with this difference, that v represents the allowable loss of potential in the magnets, and not the potential at the poles of the machine as in the case of the shunt magnets.

In regard to the mean length l_m for an assumed thickness c of a coil, the same that was said for shunt machines applies to series machines as well.

The precautions required for calculating the proper diameter d for shunt machines, in order that the resistance shall not be too great to take the current, are evidently not necessary in this case, as the whole current is compelled to go through the magnet coils. If the resistance should be a little too high, it will only reduce the efficiency of the machine, but will not prevent its working, as it would in case of shunt machines. The factor of safety referred to in calculating shunt magnets may therefore either be safely omitted, or may be taken smaller than before. The latter is preferable, as it is always more satisfactory to the constructor to find the final results to be inside of the limit placed than beyond it.

The factor of self-induction in the coils, which acts to apparently increase their resistance, is probably the most important to allow for in this factor of safety. It is not

possible to say how much should be allowed for this, as it depends on so many quantities, such as the number of windings, the number of coils on the armature, the speed of rotation, the current in the coils and the nature of the iron. For ordinary machines 5 to 10 per cent. will probably be a sufficient factor of safety to cover all these. Therefore, instead of introducing the value of v directly into the formula, substitute for it 95 to 90 per cent. of v.

Taking, as before, the value of θ equal to ·0162, and assuming a temperature of 70° F., the formula becomes

$$d = \sqrt{\frac{\cdot 875\ (a\ \mathrm{W})\ l_m}{v}},$$

in which d is in mils, l_m in inches, and v the allowable loss of potential in volts, which should first be reduced as described above, to include the factor of safety.

But this may give a diameter which is so small that the wire will heat, which will in general be the case if the magnets or the ampère-windings are small, or if the allowable fall of potential is large. In such cases, the diameter will have to be determined by the heating effect, and not by the allowable resistance. It is necessary, therefore, to calculate the proper diameter not only from the above formula, but also from the heating effect, and then take the larger value of the two. To guard against heating it is safe to take as a maximum about ·001 to ·0013 ampère per square mil of cross section of wire, which is equal to about 1000 to 1300 ampères per square inch. This, as will be noticed, is smaller than that given for shunt machines, for in the latter the wire, presenting more surface, will cool off more rapidly. For large, compactly-wound magnets, however, the difference in cooling of large and small wires will not be great, so that both this constant and the other may be varied slightly.

Having found the two values of d, and chosen the largest, take the nearest gauge number or size, to this value, and find its diameter d_1 outside of the insulation. Having given the number of magnets and the length of one magnet core e,

the number of windings per layer can then be calculated from the formula

$$\frac{1000\ e}{d_1},$$

in which e is the length of a core in inches, and d_1 the external diameter of the wire in mils.

The number of layers in this case must be calculated from the number of windings, and not, as in the shunt machine, from the allowable thickness of coil c, for in series magnets the value of W is determined at the outset by the current a, and the ampère-turns (a W), and there is no deviation from it.

The thickness c must therefore be calculated from W as follows: Let n be the number of magnets, then the turns per magnet will be $\frac{W}{n}$, and the number of layers will be

$$\frac{W}{n} \times \frac{d_1}{1000\ e},$$

from which the thickness c can be readily calculated by multiplying this by d_1 and reducing to inches. It can be calculated directly from the formula—

$$c = \frac{W\ d_1}{1{,}000{,}000\ e\ n}.$$

If this is found to be about the same thickness as that which was assumed, then (provided the wire does not heat, and the magnets are not over-saturated), the machine is properly proportioned, and there remains only to calculate the resistance or fall of potential as a check, and perhaps to alter some parts slightly for the sake of the appearance of the magnets, that is, that they may be wound full. This will be described later.

If this calculated value of the thickness c is found to be much smaller than the assumed thickness, and if it is found from the magnetism curve, as described in Chapter II., that the magnets are not over-saturated, then it shows that the

magnets are too long, and they may be advantageously shortened. The cores may be shortened to such an extent that for the same ampère-turns and diameter of wire, the thickness of coil c is about that which was above assumed; that is, the length e of a magnet in inches, may be made

$$e = \frac{W\, d_1^2}{1{,}000{,}000.\, n\, c}.$$

If, on the other hand, the thickness of the coils found from the formula is much larger, and the magnets are not over-saturated, it shows that the magnet cores are too short, and that they should be lengthened to the amount required by the formula just given.

If the magnets are very much over-saturated, it remains only to use the machine uneconomically, or to use it for less lamps, or to increase the size of the core so that from the magnetic curve the magnets are found to be just saturated. For instance, from the magnetic curve find at what point, that is, for what ampère-windings, the magnets are saturated. Divide this by the number of magnets, and then by the cross-section of a core in square inches; this gives the saturation co-efficient, or the allowable ampère-windings per square inch of magnet core, for that shape of core and for that quality of iron. Having determined this constant, it is easy to calculate what the size of core should be in order not to be over-saturated for that number of ampère-turns which this particular machine requires. If m is this allowable density of magnetism, the required cross-section in inches should be $\frac{(a\ W)}{m\ n}$.

This formula must, however, be used only for a slight increase or decrease of the size of the core, as it is only approximately correct, and it may, for an increase in the size of the core, be safely taken a trifle smaller, because, when the core is increased in cross-section, it will no longer take the same number of ampère-windings to produce the same amount of magnetism than when over-saturated as it was in determining the ampère-turns. It will then also require

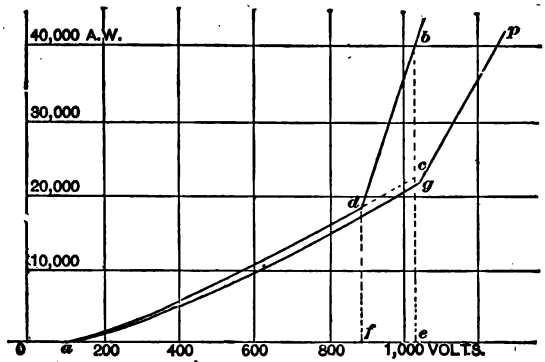
less ampère-windings to generate the same magnetism, for the reason that the same current passing through a coil with a larger core, but with the same ampère-turns, will produce more magnetism in the proportion of its linear dimensions, and therefore will require less ampère-windings to produce the same magnetism. This can be demonstrated as follows: In a single winding, the intensity of magnetism produced by a certain current is less in proportion as the diameter is increased, that is, for twice the diameter it is half as great; but the total magnetism is proportional to the product of the intensity and the area, and is, therefore, proportional to the linear dimension, because the area increases as the square of the diameter and the intensity inversely as the diameter; therefore, the total number of lines of force will increase as the diameter. For instance, if the diameter of a coil is doubled, the intensity will be halved, but as the area inclosed is four times as large, the total magnetism, being the intensity multiplied by the area, is twice as great.

For this reason, and because there will be less ampère-turns required in the new cores when they are not oversaturated, it will be better, when the increase is comparatively great, to determine the new cross-section more accurately, than by the first method, by proceeding as follows:

In the curve of magnetism *a b* in Fig. 2, below the saturation point *d*, continue the part *a d* with about the same rate of curvature, beyond the point *d*, where it takes a decidedly different direction. This will then be approximately the curve which the machine would have if the magnets were not saturated, but at the same time, if the area of core were the same. Through this new curve drop a perpendicular *b e* (representing the magnetisation) on to the line *o e*, through the point *b* at which the machine was tested for the ampère-windings required for full load, then the point *c*, where this line intersects the new curve, will give the ampère-windings represented by *c e*, which would be required on the new machine to produce the same mag-

netisation if the cores were not over-saturated, and if they were of the same size. Call this number of ampère-turns (a W') as represented by the length of the line $c\ e$; call the

FIG. 2.



distance $d\ f$, (a W''), and let the number of ampère-windings required for the new machine with larger cores be (a W); then

$$(a\ \mathrm{W}) = \sqrt[3]{(a\ \mathrm{W}')^2\,(a\ \mathrm{W}'')};$$

thus giving the required number of ampère-windings directly. This formula gives the number of ampère-windings which will be required by a larger core, to generate the same total number of lines of force, at the same allowable density of magnetisation (or co-efficient of saturation), and takes into account the fact, that, the larger the area of the core the less will be the number of ampère-windings required to generate the same number of lines of force. The application of the formula will be illustrated below by an example.

Having ascertained the number of ampère-windings, find the new cross-section of core, by dividing this by the number of magnets and by the co-efficient of saturation obtained from (a W'') and from the area of the old cores.

If the cores in the original machine are found to be very far from being saturated, the magnets are unnecessarily large

in cross-section, and they may be decreased similarly as above described for an increase.

Having determined the proper cross-section of the magnet cores for the new machine, calculate from the new number of ampère-windings (a W) what the diameter of wire should be, and from this as before, the thickness c. This will then be the thickness required when the new magnets are just saturated, and if this is much larger or smaller than the new assumed thickness, it shows that the magnet cores are too short or too long, as above described. The new length may be determined directly, without first calculating c, by the formula previously given.

If the curve of magnetisation is found to be a regularly curving line without an abrupt change of curvature, it shows that either the iron is very hard, or that it is not well distributed in the frame, or in other words, that the saturation point is not reached in all the iron parts at the same degree of magnetisation, but that at some parts the iron is too small in cross-section, and therefore saturates sooner than in other parts. Throughout the machine all the parts of the complete circuit of the lines of force should have the same degree of magnetisation, if they have not, then some parts are too large or others too small. If the iron is soft and the curve does not show one decided point of saturation, there are no doubt some wrong proportions in the sizes of the iron masses. There is no objection to having too much iron at any point, except that it makes the machine uselessly heavy, and therefore it is not of the most economical proportions.

If the curve shows no decided point of saturation and it cannot be discovered where the weak point in the magnetic circuit lies, then the magnetisation may be continued up to what seems from the curve to be the limit of economical magnetism, or for cast-iron oval magnets, up to about 240 to 250 ampère-turns per square inch of core.

Having found, as described, that the cores are not too large or too small, and having calculated the proper value of the

diameter of the wire from the allowable fall of potential and the ampère-turns, and having also guarded against heating, there remains only to provide that the last layer may be wound full, for the sake of appearance. This may be done in the case in which there are only a few turns more or less than what would be required to make it full, by simply winding it full and varying the speed slightly to compensate for this, if necessary. If, however, this difference is comparatively great, it is best to proceed as follows: Calculate the number of turns which would come on the last incomplete layer, wind this number of turns on the next to the last layer, filling up the remaining space with cardboard or something similar, to the thickness of one layer, and then wind the last layer full over all. It may also be done by winding the odd number of turns in a coarse or open spiral in the next to the last layer, and then cover this with a sheet of stiff cardboard, over which the last layer may be wound full. This, however, is not as good as the first method, as the cardboard, if not very stiff, is apt to cave in.

Having made all the necessary calculations for the diameter of the wire, it is best to check the result by ascertaining the loss of potential for the wire selected, and to compare this with the allowable loss. To do this, calculate the corrected mean length of one winding l_m, in inches. The resistance will then be:

$$R = \frac{50 \cdot 13 \; W \; l_m \; \theta}{d^2},$$

then from Ohm's law and from this equation, the fall of potential in the whole magnet circuit will be:

$$v = \frac{50 \cdot 13 \; (a \; W), \; l_m \; \theta}{d^2},$$

which for $\theta = 0 \cdot 0162$ and a temperature of 70° Fahr. becomes:

$$v = \frac{\cdot 875 \; (a \; W) \; l_m}{d^2} = \frac{3 \cdot 5 \; (a \; W) \; l_m}{4 \, d^2},$$

in which d is in mils and l_m is the corrected mean length of one winding in inches.

If this gives a value much higher than that which was allowed, owing to the fact that the smaller gauge number wire nearest to the theoretical value obtained by the formula was taken, then if the difference is too great to be admissible; the next size larger may safely be taken without necessitating any other change in dimensions.

When the machine is completed and is run on its proper circuit, if it is desired to make the final accurate adjustment, it is only necessary to increase or diminish the speed by a few turns. This may be calculated from the final test by taking the speed proportional to the potential, provided the current strength was correct. If both the current and potential are slightly incorrect, alter the external resistance until the current is correct, then measure the potential and proceed as before. Care should be taken that the machine is warm throughout before making the measurements. If the machine is properly calculated, these final adjustments will be very slight in most cases, and will, therefore, generally be found unnecessary.

If it is desired to regulate the machine to generate the same current with different potentials, that is, to run a varying number of arc lamps, place an adjustable resistance in multiple arc (as a shunt) with the magnet coils. This will shunt off some of the current from the magnets, and will enable one to regulate the magnetism and therefore to adjust for a varying number of lamps.

If this is to be done, make the first test for both the maximum and minimum number of lamps, noting the ampère-windings required in both cases. Calculate and complete the machine just as before, from the larger of these two numbers of ampère-turns. The current required for the magnets in the two cases will evidently be proportional to the ampère-windings, as the number of windings is the same. This gives the current required in the magnets when the smaller number of lamps are run, from which,

having calculated the resistance of the coils, it is easy to calculate what the adjustable resistance should be in order that the proper amount of current is shunted off by it, for the currents will be approximately inversely as the two resistances.

This may be done as follows:—

If the normal current of the machine is a and the ampère-turns required in the two extreme cases are (a W) and (a' W) then the current required in the magnets for the small load is approximately

$$a' = \frac{(a' \text{ W})}{(a \text{ W})} a,$$

and if R is the total resistance of the coils and r the minimum adjustable resistance for the small load, then

$$r = \frac{a'}{a - a'} \text{R}.$$

The maximum adjustable resistance depends on whether the machine is to be regulated near its full load, in which case the maximum resistance can be calculated similarly to the above.

As the winding of the magnets is entirely independent of this resistance, a less troublesome and sufficiently accurate method of determining the adjustable resistance is to run the finished machine with loads varying from the full load down to a short circuit, and, every time the load is reduced, adjusting any convenient resistance which shunts the magnets, until the proper current in the external circuit is obtained. Measure these resistances for each case and calculate the adjustable rheostat wire from this, taking care to proportion their diameters, so that they will not heat too much, and at the same time not require too much wire. The current going through the rheostat can be readily calculated for each case from the resistance of the magnets and the resistance of the shunt rheostat.

To illustrate the method of calculating the winding of a series machine, assume the following data:—

An arc light, series-wound machine is to be built for a 10 ampère current at 1000 volts, for about 20–23 lamps. Speed, 1200 revolutions.

The armature was constructed and a trial frame built. Upon running the machine with four temporary coils of 250 windings each, it was found to require an exciting current of 40 ampères to bring the current of the machine up to 10 ampères and 1000 + 2·5 per cent. of 1000 = 1025 volts. This gives $250 \times 4 \times 40 = 40{,}000$ ampère-windings as a measure of the magnetism required.

The oval cast-iron cores were $8\frac{1}{2} \times 2\frac{3}{4}$ inches. The assumed thickness of a coil is $\frac{1}{3}$ of $2\frac{3}{4}$, or about 1 inch. The periphery of core was found to be 18·8 inches. This gives, from the formula in Chapter III., a mean length of one winding equal to 22·1 inches. From the formula for the diameter of the wire of the magnets,

$$d = \sqrt{\frac{\cdot 875\ (a\ \mathrm{W})\ l_m}{v}},$$

taking the allowable fall of potential equal to 25 volts, and assuming a factor of safety of 5 per cent., therefore making v = 95 per cent. of 25 = 23·8 volts, the diameter will be,

$$d = 181 \text{ mils.}$$

This is about a No. 5 B. & S. (about a No. 7 B.W.G.). The heating will not be too great, for, from the allowable density of current, a No. 9 wire would answer.

No. 5 wire was found to have an outside diameter of 220 mils. The length of a core being 10 inches there will be 45 windings per layer. As there must be 40,000 ampère-windings, and being a series machine, and the current in the magnets being 10 ampères, there will be 4000 windings, or 1000 per magnet, making 22 layers, and a thickness of coil of $4\frac{3}{4}$ inches, as compared with the assumed thickness of

1 inch. This apparently absurd result shows that the magnets are very much too small, and that it would hardly be possible to finish the machine for such a large load. This might have been seen from the magnetic curve, but for the sake of illustration the calculations were also made.

The figures obtained will, however, not only show what load this machine will carry, but will also enable one to calculate about what the size of the magnets should be for another machine which will give 1000 volts and 10 ampères.

To determine the first, let *a b*, Fig. 2, be the curve of magnetisation for this machine, obtained as described in Chapter II. It will be seen from this curve that the magnets are saturated at about 18,000 ampère-turns, and unless it is intended to over-saturate the cores to obtain greater steadiness in the current, this will be the maximum magnetism which ought to be used. Dropping perpendiculars from *b* and *d*, the distance *o e* will represent 1025 volts, and *o f* will be the greater number of volts which the machine will give if not over-saturated, provided that the required number of ampère-windings will not make the coils too thick. The distance *o f*, measured with the same scale, was found to be about 880 volts.

Calculate the diameter *d* again for 18,000 ampère-turns, and an allowable loss of potential of 2·5 per cent. of 880 gives

$$d = 128{\cdot}4 \text{ mils.}$$

This is almost exactly No. 8 B. & S. (or about a No. 10½ B.W.G.). This will be found to be large enough not to heat too much. Its external diameter is about 158 mils. There will be 63 windings per layer, and about 7 layers, making a thickness of coil of 1·1 inch. This is about the assumed thickness of 1 inch, and shows that the machine is properly proportioned.

To check the result, calculate the fall of potential with a No. 8 wire and a thickness of 1·1 inch. This gives from the formula

$$v = \frac{{\cdot}875\ (a\ \mathrm{W})\ l_m}{d^2} = 21{\cdot}3 \text{ volts.}$$

This is within the limit of 22 volts, showing the calculations to be correct.

It is evident that another armature with more turns of wire might be used with the same frame, thus obtaining a higher potential with the same magnetisation, or the same potential with less magnetisation. Whether this is to be recommended depends upon the nature of the armature used in the test, and belongs to the subject of armatures; it cannot therefore be discussed here. It is assumed here that the armature has been determined.

Let us now determine from the above test approximately what the size of the magnets should be for a new machine with the same armature, but giving the full potential of 1025 volts, which was what it was originally intended for.

From the point *d*, Fig. 2, and from the size of the core, determine the saturation co-efficient, or the allowable density of magnetisation for this particular quality of iron. As there are necessary for saturation, 18,000 ampère-turns, and as there are four magnets, if one-fourth of this is divided by the number of square inches in the cross-section of the core, viz., 18, it will be the allowable density or saturation co-efficient. This gives 250 ampère-windings per square inch. The cross-section of the new magnets must therefore be such that the density of magnetisation, as determined from the new number of ampère-turns, does not exceed 250 per square inch.

To determine the ampère-turns for the new magnets, prolong the part of the curve *a d*, Fig. 2, until it intersects the line *b e* at a point *c*; then *c e* will represent the magnetism which would be required for 1025 volts with the old magnets, if they were not over-saturated, as *b e* represents the ampère-turns required for 1025 volts with the old machine in which the magnets are over-saturated.

The distance *c e* represents about 22,650 ampère-turns, while *d f*, the allowable magnetisation for the small cores, is 18,000. Calling the latter (*a* W″) and *c e* the former (*a* W′)

while the required number of ampère-windings is represented by (a W), then, from the formula, the value of (a W) is

$$(a\ \mathrm{W}) = \sqrt[3]{(a\ \mathrm{W}')^2\ (a\ \mathrm{W}'')} = 21{,}000.$$

This makes the new cross-section

$$\frac{21{,}000}{4 \times 250} = 21 \text{ square inches.}$$

The dimensions of the oval cores should therefore be about 3 × 9 inches. The diameter of the wire will be, assuming a thickness of coil of about 1 inch,

$$d = 134 \text{ mils,}$$

or about No. 8 B. & S. (or about a No. 10½ B.W.G.). This will not heat too much, as it is larger than that given by the allowable density of current. As a No. 8 wire has an outside diameter of about 158 mils, there will be 7 layers for a thickness of about 1 inch. This gives

$$\frac{21{,}000}{4 \times 7} = 75 \text{ turns per layer,}$$

making the new cores 75 × ·158 = 12 inches long.

The curve of magnetisation for the new magnets would be about as shown by $a\ g\ p$ in Fig. 2.

To check the result, calculate the fall of potential from the formula, which gives

$$v = 26 \text{ volts,}$$

or only a trifle higher than what was assumed at the outset. This results from having chosen the next smaller size wire to that given by the formula.

Suppose the finished machine gave only 990 volts and 10 ampères, then the speed should be increased to

$$\frac{1200 \times 1000}{990} = 1212 \text{ revolutions.}$$

CHAPTER V.

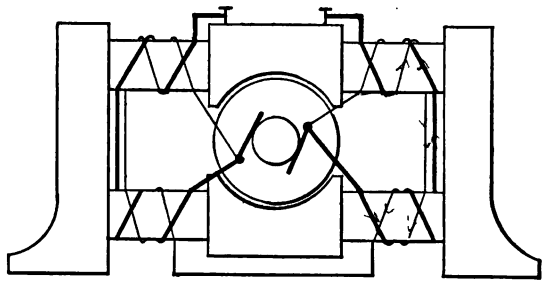
Compound Machines.

The general principle of the compound winding is as follows: In a simple shunt machine, the greater the current in the external circuit or in the armature, the greater will be the fall of potential in the armature itself, due to its resistance, and therefore the loss will be the difference of potential at the terminals of the shunt coils. This decreases the current in them, thus diminishing the magnetism, which again decreases the potential. The potential at the poles of the shunt machine must, therefore, fall a certain definite amount with an increase in the number of lamps in circuit. When the armature resistance is very small, this decrease of potential will be correspondingly small. The increased "counter-magnetism" of the armature, due to its own current, also tends to decrease the potential for an increased current. If by some means these losses of potential, due to an increased current, could be generated again automatically by an exactly equal amount by increasing the magnetism proportionally, it is evident that the potential at the poles could be made to remain constant or nearly so. This may be done by adding series coils to such an amount that the total magnetism of the field increases with an increasing current in the external circuit, thus maintaining constant the potential at the poles of the machine.

The connections of the shunt coils may be made in one of two ways. In the first of these, called the ordinary compound machine connections, and shown in Fig. 3, the terminals of the shunt coils are connected to the poles of the armature, or, what is the same thing, to the brushes. The current in the series coils is, therefore, not the total current of the armature, but is the current in the external circuit, or, what is the same thing, the armature current less the shunt current. When no lamps are burning,

the series coils are idle, the shunt coils alone being used to keep the machine at its proper potential. If the potential at the poles of the machine is constant for varying loads, it will not be so at the poles of the armature or at the brushes, and,

FIG. 3.



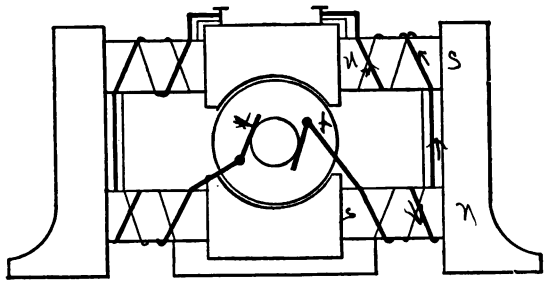
Ordinary Compound Winding.

therefore, not at all the terminals of the shunt coils. The potential at the latter will be equal to that at the poles of the machine, increased by that which is absorbed in the series coils, which latter quantity is evidently the current in the external circle multiplied by the resistance of the series coils, and is, therefore, a variable quantity depending on the number of lamps in circuit. The current in the shunt coils is, therefore, not constant, but depends to a small extent on the number of lamps burning and on the resistance of the series coils.

The second system of connecting the coils is called by Prof. S. P. Thompson the "long shunt" method, and is shown in Fig. 4. The terminals of the shunt coils are not connected to the brushes as before, but to the poles of the machine. The potential at these points being constant, the current in the shunt coils is constant for all loads, and represents, therefore, a constant magnetisation such as from steel magnets or from a separate exciting machine. The current in the series coils is in this mode of connecting, the whole current of the armature, because the current passes from the

brushes directly into the series coils and afterward divides between that in the external circuit and that in the shunt. The series coils act to a certain extent both as series and shunt coils, as the current in the shunt coils flows through

FIG. 4.



"Long Shunt" Compound Winding.

the series coils as well, and when the machine is on open circuit, the shunt current has to flow through the series coils first, thus making them act as shunt coils also.

It is a question which of these two systems is more economical as regards material, operation and construction, though it is probable that the second or "long shunt" method is the better. In regard to economy of material the second is probably cheaper, for although there is a trifle more lost space between the wires, owing to the thicker wire of the series coils, yet there is less space and material wasted in the insulation, for suppose a thin shunt wire and a thick series wire were wound side by side to take the place of the single series wire of the second method which carries both these currents, the two wires would evidently take up more room and would cost more in material than the one thick wire, although answering the same purpose. In regard to the economy of operation of the two systems there is probably very little difference. There may be a slight difference in favour of the "long shunt" method because the magnets will be slightly less bulky. In regard to economy of construction,

there is less work required to wind the magnets in the second case, as there are always less windings in all. If certain errors in the calculations which may often be neglected, are corrected, the long shunt method becomes somewhat easier to calculate than the ordinary. In many cases, especially for large, well-proportioned machines, there will be very little practical difference between the two methods.

The preliminary test of the machine, preceding the calculations for the proper proportions of the series and shunt coils for either the ordinary or the long shunt method, is the same for both, and is made as follows, independently of the method of winding which will be used.

Make the test for determining the magnetism, with temporary coils and a separate exciting machine, in the same way as was described for shunt machines, only that instead of making but one test for full load, make a series of tests (as many as practicable—say fifteen to twenty) beginning with a little more than full load, and continuing by diminishing the number of lamps down to an open circuit. For each different number of lamps, adjust the exciting current until the potential is the required amount, and then measure both the exciting current and that in the lamp circuit, being careful that the speed remains the same, for with a poorly governed engine the speed is likely to increase as the number of lights diminishes. The speed should be noted, and *must not be changed*, as the proportioning of the coils is different for different speeds. The machine should be run for a time on full load, or even more, so as to become warm throughout.

In the absence of a reliable ampère-meter for such a large range as is required for the current in the external circuit, it is sufficiently accurate, if the incandescent lamps are uniform, to calculate the current in the external circuit from the number of lamps, by measuring accurately, once for all (and with the same instrument to be used for the exciting current), the current required by a large number of lamps *at their proper potential*, and dividing this by their number.

This constant gives the current per lamp, and can be used to calculate the currents for the decreasing number of lamps. Even if the constant of the instrument is not quite correct, the relative values of the lamp current and the exciting current are correct, and the test will give values which will answer the purpose. It is important to adjust accurately for the proper potential in each case, otherwise the results will be very unsatisfactory.

Before making this series of measurements, it is advisable to examine the necessary shifting of the diameter of commutation. To do this, run the machine at full load at the proper potential, and adjust the brushes to the non-sparking position, then disconnect all but a few of the lamps, and run it again at the proper potential by changing the exciting current, and find the non-sparking position of the brushes again. If the change of position is very great, it is not advisable to attempt to make the machine a self-regulating compound machine, as it will be very unsatisfactory; in fact it will evidently not be automatic if the brushes require to be adjusted. If the change of position is great, there are some bad proportions in the machine, at least, for a compound machine. Probably it is the fault of the armature, as it may have too many windings, or its iron may be too hard, or there may be too few coils or commutator bars, the self-induction being too great. It may also be the fault of the pole-pieces, as they may be too wide in the direction of rotation. It might be due to an unbalanced field having the iron unsymmetrically placed in the form of arms, bearings, base, &c. The brushes should not touch more than two, or at the most, three commutator strips at one time, and they should be precisely diametrically opposite each other. General hints in regard to the best proportions, to prevent the shifting of brushes, will be given in the latter part of this chapter.

If the change of position of the brushes is more than about one-half an inch, on a commutator of about four inches diameter, the machine is not well proportioned. A good

compound machine ought not to spark or require the brushes to be moved, even for a sudden change from a full load to an open circuit or the reverse. They should be moved only when worn off. It is, of course, taken for granted that the contact surface of the brushes is more than the thickness of one insulation between two commutator bars, and that they are exactly diametrically opposite each other. If the brushes need slight adjusting, it is best to find a mean position and keep them there for all loads, provided they do not spark too much to injure the machine for the extreme loads.

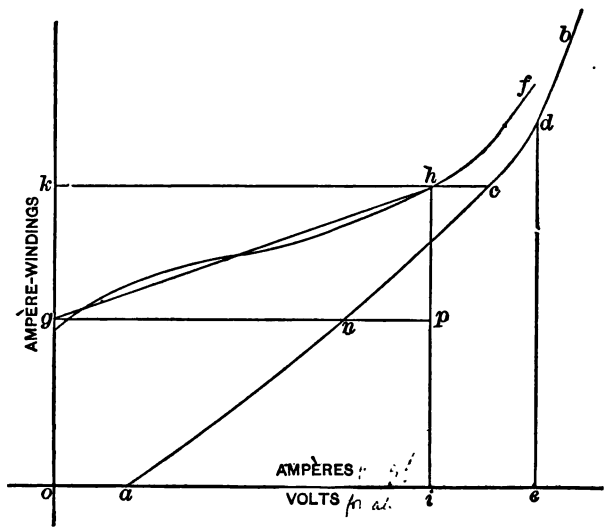
Having found this position and marked it, the test for determining the ampère-windings may be made as above described, the results giving the required exciting current for each different number of lamps to bring the machine to its desired potential. This current multiplied by the number of windings of the temporary coils, gives the numbers of ampère-windings required for supplying a constant potential to a varying number of lamps.

Having made all these adjustments and the series of measurements for determining the ampère-turns for different numbers of lamps, it is advisable, though not absolutely necessary, to make the other test for determining the magnetic curve, as described in Chapter II. It is more necessary to do this in the case of compound machines than for either shunt or series, as it enables one to see up to what limit the machine may be made to have a constant potential, and also to see whether it is practicable to attempt to make it compound at all. If there is any doubt about its being well proportioned for a compound machine, it is best to make this test first, in order to save the trouble of making the other test in case the proportions are found to be too bad for a compound machine. How to improve the proportions from the results of this test will be discussed in another part of this chapter.

From the results of this test for the relation between the useful magnetism and the ampère-windings, lay off the

values of the potential on open circuit and the magnetising ampère-windings as abscissas and ordinates respectively, and draw the curve through the points in the same way as described in Chapter II. If the machine is properly proportioned, this curve should be two tolerably straight lines connected by a short curved line, as in *a b* Fig. 5.

FIG. 5.



As the ampère-windings must, from the nature of the compound winding, increase in direct proportion to the current of the machine, it is evident that the machine may be made compound only on one or the other side of the curved part *c d* of the line *a b*; that is, for the curve represented here, the extreme number of ampère-windings must be equal to or less than that for the point *c*,—that is, equal to or less than *k o* or *h i*, or the smallest limit must be equal to or greater than that for the point *d*,—that is, *d e*. It cannot possibly be made to have a constant potential for a

number of ampère-windings lying between *c* and *d*, except, perhaps, approximately for a very short range, if the curve is not a sharp one. As the point *c* designates the point at which the magnet cores are just being saturated, it will evidently be more economical to run the machine between the points *a* and *c*, rather than between *d* and *b*, for it will then require less energy in the magnets, and therefore also less wire, the amount of thick wire (series coils) being very much less for points below *c* than for points above *d*. If the curve is not even approximately straight at one of the two parts, it is not advisable to attempt to make the machine self-regulating with a constant potential without adjusting the brushes, except for very small ranges of the varying load. In general, the straighter this curve below the saturation point *c*, the more nearly can the machine be made to have a constant potential.

Having made this examination and found the maximum limit to the number of ampère-turns, take the results of the test first described, for determining the ampère-windings required for supplying the same potential to different numbers of lamps, and construct a curve from the values obtained, by laying off the current of the armature as abscissas, and the required number of ampère-windings as ordinates, plotting the points and drawing a line through them. This line will generally be somewhat like the curved line *g f* in Fig. 5, and may, for the sake of direct comparison, be drawn on the same sheet with the other curve, by taking the abscissas as ampères instead of volts. The line *c k* representing the permissible limiting value for the ampère-windings, shows, by its intersection *h* with the curve *g f*, the extreme number of ampères *h k* or *i o*, for which the machine may be made self-regulating. The line *g n* shows the smallest number of ampère-turns which will ever be required (on open circuit), and, therefore, by its intersection with *a c* at *n* shows the limiting portion *n c* of the curve *a c*, which is in actual use. If this part *n c* of the curve *a c* (which, under good conditions, will be very small), be

straight, or nearly so, the machine may be made self-regulating, even if the rest of the curve *a b* is very much curved. This portion *n c* may be made quite small by making both the armature resistance and the number of turns on it small, the field intense and the number of armature coils large, as will be shown in another part of this chapter.

It may be remarked here, that if the test had been continued for a greater number of lamps than that which is represented by the distance *o i*, the curve *g h* would have been found to curve upward like *h f*, due to the fact that the magnets are being saturated. The machine can be made self-regulating only for the tolerably straight portion of the whole curve *g f*. Furthermore, if *n c* is curved considerably, *g h* will also be so in about the same proportion and in the same direction.

To calculate the number of ampère-windings which must be allotted to the shunt and to the series coils, draw a straight light line *g h* through the curved line *g h*, making it coincide more nearly with those portions of the curve which represent the numbers of lamps which will be used most frequently with that machine. For instance, at or near *g* the curve will probably deviate most from the straight line, but it is not necessary to consider that part of the curve, as the machine will probably seldom be used for such a small number of lamps.

The vertical distances to this straight line *g h* represent the ampère-windings which can be supplied by a winding consisting of series and shunt coils, and is, therefore, the nearest approach possible with such a winding to generate the ampère-windings required by the curved line *g h* obtained from the test. The more this straight line deviates from the curved one, the greater will be the deviation of the potential from the desired constant value.

From the position of this line the proportion of the series and shunt coils is calculated as follows. It is evident that the vertical distances, representing ampère-turns, are made up of a constant part *g o* and a regularly increasing part

lying between *g h* and the horizontal line *g p*. It is evident, therefore, that the shunt coils—in which, as was described, the current is approximately constant for any number of lamps—must supply the ampère-windings represented by *g o*, and the series coils must supply the constantly increasing portion between *g p* and *g h*.

Up to this point it is immaterial which of the two methods of winding is to be used. In many cases it will make so little difference whether the long shunt or the ordinary method is used, that the same calculation will answer for both. Furthermore, if it is not necessary to make the machine regulate automatically as accurately as it is possible to make it, then certain corrections may be neglected, in which case also the same calculation will answer for both methods.

The conditions under which the following calculation can be used for both cases are as follows:—If the machine is large; if the relative armature resistance is small; if the proportion of energy required in the magnets is not too large; if the shunt current may be comparatively small; if the brushes may be shifted slightly to adjust for potential; if an adjustable resistance in the shunt current may be used within small limits; if the magnets are not over-saturated; if the speed is not quite constant, thus necessitating hand regulation.

Under these conditions the following approximate method may be used. The shunt coils are calculated in the same way as for an ordinary shunt machine from the number of ampère-windings represented by the distance *g o*, the only difference being that the current for this shunt-winding is a smaller proportion of the whole current than in ordinary shunt machines. The series coils are calculated as follows:—For a current in the armature represented by *o i* the number of ampère-windings must be increased by an amount represented by *h p* ampère-windings in addition to that supplied by the shunt magnets, and represented by *p i* or *g o*. As this same current *o i* flows through these series coils as well as

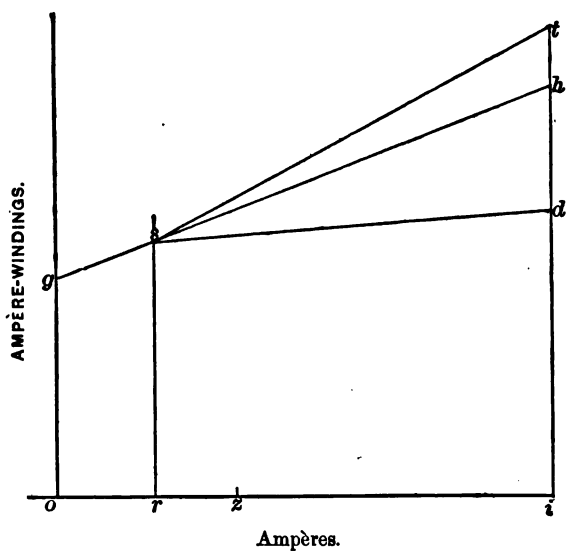
through the external circuit, it is evident that the number of windings of the series coils must be this number of ampère-windings represented by $h\,p$, divided by the current represented by $o\,i$. The number of windings thus obtained will evidently be the same, no matter what the current is, as it depends only on the angle $h\,g\,p$. The diameter of the wire must be calculated as for an ordinary series machine, from the maximum current $o\,i$, and the allowable fall of potential which in this case must be much smaller than in a series machine. In general, the whole allowable loss of energy for the magnets can be divided into two parts, which have the proportion which the distances $h\,p$ and $p\,i$ have to each other and to the whole distance $h\,i$, giving the series coils that part $h\,p$ of the whole $h\,i$, and allowing the rest $p\,i$ for the shunt. For instance, if $h\,p$ were one-third of $h\,i$, then the series coils may absorb about one-third of the whole amount of energy allowed for the magnets and the shunt coils the remaining two-thirds. If 3 per cent. of the whole energy is allowed for the magnetisation, then in this case the series coils may absorb 1 per cent. of the potential, and the shunt coils 2 per cent. of the maximum current.

As will be noticed, this method does not take into account the fact that the loss of potential in the series windings should be replaced by an increasing potential at the armature; neither does it take into account that the shunt coil current should be subtracted from that in the external circuit and in the series coils. Therefore the potential at the poles of the finished machine, although approximately constant, will not approach as closely to a constant potential as it would be possible to make it if the proportions of the windings were corrected for these losses. These corrections become all the more necessary, in fact sometimes quite essential, under the following conditions: if the machine is small they are essential; if the armature resistance is relatively high, that is, if the series coils supply a great part of the ampère-windings, the correction for loss of potential is important; if the magnets are over-saturated this correction

generally becomes essential; if the required magnetisation is relatively great, and the shunt current relatively large, the correction for this shunt current is important; in general, if the proportion of energy required by the magnets is large, both corrections become necessary. If constant speed can be maintained, and it is required to make the machine have as nearly a constant potential as it is possible to make it, then both corrections should be made.

These corrections will evidently be different in the two methods of winding. For the ordinary compound winding shown in Fig. 3, in which the shunt coils are attached to the poles of the armature, let *g h*, Fig. 6, represent the same line

FIG. 6.



as *g h* in Fig. 5. In the same way as before, determine approximately the current required for the shunt circuit and the loss of potential allowed for the series coils. Lay off *o r* equal to the shunt current (exaggerated in this diagram for

the sake of clearness), then $r\ s$ will represent the ampère-turns required in order to supply the necessary current for the shunt when the machine gives the proper potential on an open circuit. The currents in the lamp circuit will, therefore, be measured from r to the right; that is, they are equal to the whole armature current, $o\ i$ for instance, less that used in the shunt $o\ r$.

When the current flows through the lamps, and therefore through the series winding, the potential at the poles of the machine would fall by the amount which is absorbed by the series coils, for in the test the machine was run with constant potential at the armature. As this fall of potential increases with the current, it will have to be generated again by a corresponding increase in the number of series windings. Furthermore, as this fall of potential does not begin until the series coils begin to act, a line $s\ t$ drawn from s making a certain small angle with $s\ h$, would represent the necessary increase of the ampère-windings in order to increase the potential at the armature, so that at the poles of the machine it may be constant. Furthermore, if the potential at the armature poles be increased, the current in the shunt will be increased, for it is connected to these poles. The question then arises, how many of the ampère-windings will remain for the series coils to generate. This may be calculated as follows:—From the allowable loss of potential in the series coils at the maximum load, calculate by simple proportion what the total increased number of ampère-turns must be; in other words, if the constant potential V volts requires $h\ i$ ampère-windings, then $V + v$ volts (v being this loss in the series coils) will require $\frac{V + v}{V} \times (h\ i)$ ampère-windings. This gives the distance $i\ t$. Then $s\ t$ will represent the true corrected curve which gives the true values of the ampère-turns necessary to raise the potential of the armature so that the potential at the poles of the machine will remain constant.

The proportion of this which will have to be allotted to

the series coils is obtained as follows:—Knowing the highest potential at the armature, $V + v$, and calculating the resistance R of the shunt coils from the potential on open circuit and the current in it, calculate what current will flow through it at the maximum load when the potential at the armature is $V + v$. This gives for the maximum current through the shunt $\frac{V + v}{R}$, which multiplied by the shunt windings, give the ampère-windings in the shunt coils for the full load. Therefore, if this is laid off at *i d*, then it will leave *d t* ampère-windings to be supplied by the series coils. Dividing this number of ampère-windings, represented by *d t*, by the current in the external circuit (remembering to subtract that in the shunt for *d i* ampère-windings from the whole current *o i*) it will give the corrected number of windings for the series coils.

Having thus found the proper number of windings for the series coils, and having given its maximum current and its allowable resistance (from the fall of potential and maximum current), the rest of the calculations is the same as for series machines, except that in this case the series coils are limited to a much less space. In the same way, having found the maximum number of ampère-windings *i d* of the shunt coils, and having given its allowable current and the maximum potential at the armature for full load, the rest of the calculation is the same as that for ordinary shunt machines.

On account of the inflexibility of the thick wire, the series coils are generally wound first and the shunt coils over them. In that case care should be taken to correct the mean length of the shunt-windings, for what was before the space occupied by the core for an ordinary shunt machine, is now that occupied by both the core and series winding. Another way to wind the magnets is to place the series coils at one end of each, or of alternate magnets. This is not advisable, as it requires more time and care to wind them and they are likely to collapse unless held by a

guard of some sort, which occupies valuable room in the coils.

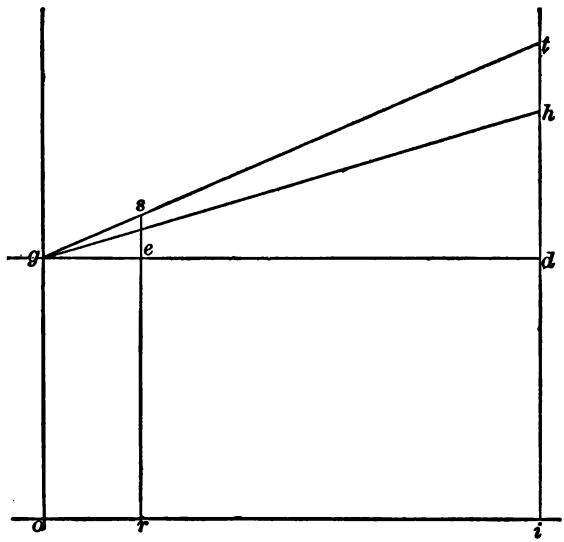
The diagram, Fig. 6, also shows at a glance how the ampère-windings are divided between the shunt and series coils. The line *s t* gives the corrected relation between the armature current and the required ampère-windings for constant potential at the poles of the machine. The space below the line *s d* will show how much of the magnetism is supplied by the shunt coils, while the space between *s d* and *s t* shows how much is supplied by the series coils. The space *s r o g* (very much exaggerated here) shows the proportion of the whole number of ampère-windings required to generate the current for the shunt coils; the space *h s t* (also exaggerated) represents that required to generate the potential lost in the series coils. If the current in the external circle were *r z*, for instance, it would be seen at a glance that the machine was running very uneconomically, as about half the energy generated is absorbed by the magnets.

For the "long shunt" winding, in which the shunt coils are connected with the poles of the machine, as shown in Fig. 4, the corrections will be somewhat different. Referring to Fig. 7, let *g h* represent, as before, the results of the experiments, as shown in Fig. 5. In the same way as before, determine approximately the loss of potential allowed for the series coils and the total number of ampère-windings which will be required to generate the proper potential plus what is lost in the series coils. Lay this off as *t i*, then *t g* will give the corrected values for the ampère-windings required.

As the whole current passes through the series coils in this case, it is evident that their action will be proportional to the armature current and not to the external circuit current, as with the ordinary compound winding. From this it follows that the ampère-windings for the shunt magnets must be that represented by *g o*, and as this is constant for any number of lamps, *g d* is in this case horizontal, leaving *d t* as the number of ampère-turns to be supplied by the series coils at maximum load. Knowing the whole current

(including shunt) at this load, the number of windings is the quotient of the two, that is, $\frac{d\,t}{o\,i}$. Having thus found the number of windings of the series coils, and having given its maximum current and its allowable resistance, the rest of the

FIG. 7.



calculation is the same as before. In the same way, having found the ampère-windings of the shunt coils, and having given its allowable current and the constant potential at the poles of the machine, the rest of the calculation is the same as before.

The diagram also shows, as before, that the space below *g d* represents the ampère-windings in the shunt; that between *g d* and *g t* represents the ampère-windings in the series coils. The space *g e r o* represents the ampère-windings required to supply the shunt current, and *g h t* that required to supply the energy lost in the series coils. The

distance *s e* represents the ampère-windings generated by the series coils on open circuit, that is, when they act together with the shunt coils as such. It will be seen, by direct comparison of Figs. 6 and 7, in what manner the proportions of the different coils will vary in the two different systems. In Fig. 7, the shunt coils are evidently smaller, and the series coils larger. In both, it will be noticed that the nearer the point *s* is to the point *g*, the more nearly alike will these two methods of winding be.

In many systems of distribution for incandescent lamps, the potential at the lamps will fall with an increased number of lamps, owing to the increased current in the leads. If it is desired to correct for this in the winding of the machine magnets, it is only necessary to increase the number of series windings by the proper amount, in order to generate the desired increase of potential at the poles, which can readily be calculated. This correction is made in the same way as that for the loss of potential in the series windings. If this correction for leads is comparatively great, care should be taken to correct the shunt winding also, on account of the increased potential at its terminals.

As will be seen from the above description, much greater care must be taken, and more accurate calculations must be made for compound machines than for ordinary shunt or series machines. A change in one quantity will affect several others; especially is this the case with the speed, which should be kept the same throughout: if it cannot be maintained constant, there is little use in attempting to make the machine more than a rough approximation to one of constant potential.

If, upon running the finished machine, it is found to give too low a potential, owing either to an error in calculation, or to the copper having a higher resistance than was assumed, a change in the speed will correct the potential for that load; but the machine will then no longer have a constant potential, as a change in speed alters the required proportion between the series and shunt coils.

If it is desired to make final adjustments, or to allow for slight errors in calculation, or for certain small changes of speed, the shunt coils may be so calculated as to have a somewhat smaller resistance than would otherwise be necessary, and an adjustable resistance placed in circuit with them. This will enable one to adjust the shunt coils. To adjust the series coils, they must be calculated for a somewhat smaller current than otherwise, and an adjustable resistance placed between the terminals of the series coils so as to shunt off a portion of the current. By this means both series and shunt coils can be adjusted or varied between certain limits, thus avoiding the necessity of great accuracy in calculation. This also allows for the correction of small unavoidable errors, and for adjustment for a slightly different speed. These adjustable resistances, after being set by experiment to their proper values, need no further alteration. From the different functions of the two coils it can readily be seen by a trial test, which of them requires to be varied in adjusting the machine.

In conclusion, let us examine the diagram Fig. 5 again, in order to see what are the best proportions for a good compound machine. As the curve of magnetisation *a c* should be as straight as possible, the magnets should be of as soft a quality of iron as possible, and should just begin to be saturated with the maximum load. They should, therefore, be large enough, and there should be no great resistance to the lines of magnetic force by a scant allowance of iron at any part of their circuit. The magnets and iron should of course be arranged as economically as possible as regards utilisation of the field.

As the armature resistance increases, the angle which the line *g h* makes with the horizontal increases, and hence also the number of series coils; in this case the deviation of the curved line *g h* obtained from experiment and the straight line assumed, becomes greater, and hence also the deviation of the finished machine from one of a constant potential. From this it is seen that it is desirable to have

the armature resistance as low as practicable, and, therefore, the field more intense, up to a certain limit. A Weston machine, exhibited at the Philadelphia Electrical Exhibition in 1884, had an armature of such low resistance that it had very nearly a constant potential for varying loads, without the use of any series winding. It is a question whether this is not the other extreme; that is, whether it would not have been more economical, as regards cost of material and construction, to make the machine somewhat smaller with a correspondingly higher armature resistance and a few series coils, at the same time letting the machine have the same efficiency and capacity.

As the self-induction of the armature coils increases the sparking, it is well to have as few turns per coil on it as possible, and a correspondingly large number of commutator strips or coils.

As the magnetic lag of the iron in the armature increases the difficulty of making the machine one of constant potential, it should be made as small as possible by having the iron of the softest quality, and the number of armature windings on it as small as practicable.

As it is very desirable not to have to shift the brushes, everything possible should be done to avoid sparking and change of position of the line of commutation, or, what is the same thing, to avoid having to change the position of the brushes. Therefore, in addition to what has been said, the field should not be unbalanced, that is, the iron and coils should be so distributed that the field is symmetrical on both sides of the armature.

Lastly, great care should be taken in constructing compound machines, for if an error or fault shows itself, it cannot be corrected as readily as in other machines by merely changing the speed, coil resistance, or position of brushes, as these changes will alter the compounding of the machine, so that it will then no longer have a constant potential.

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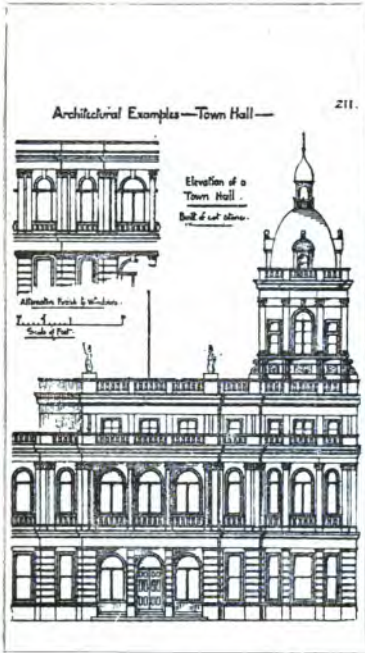

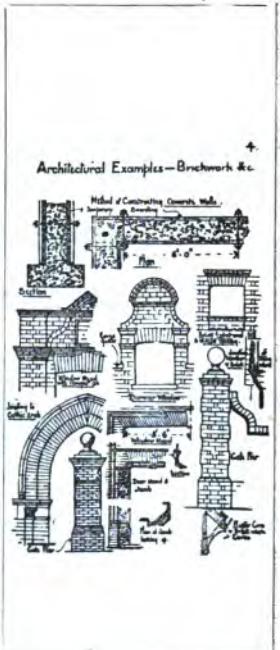

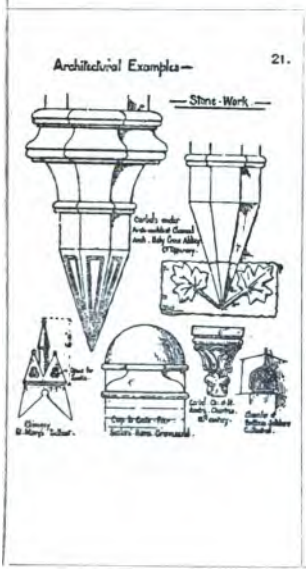

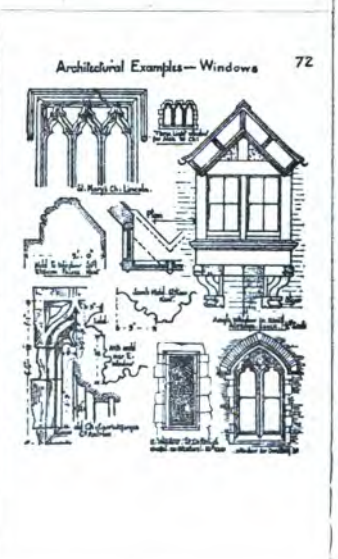

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